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COMBUSTION TESTS OF RJ-5 FUEL BLENDS

RAMJET TECHNOLOGY BRANCH
RAMJET ENGINE DIVISION

AUGUST 1976

TECHNICAL REPORT AFAPL-TR-76-54
FINAL REPORT FOR PERIOD FEBRUARY THROUGH JULY 1976

AIR FORCE AERO-PROPULSION LABORATORY
AIR FORCE WRIGHT AERONAUTICAL LABORATORIES
AIR FORCE SYSTEMS COMMAND
WRIGHT-PATTERSON AIR FORCE BASE, OHIO 45433

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An experimental investigation was conducted on the addition of viscosity reducing additives to RJ-5 fuel. The tests were to determine if the additives hindered or improved the combustion efficiency of the basic RJ-5 fuel. The tests were conducted in a 12 inch diameter dump combustor with a L/D of 4, no flameholder and a 50% nozzle at three different inlet air temperatures. The fuels employed for the tests were JP-4, RJ-5, SI-80 (20% isobutylbenze and 80% RJ-5) and HDF-2 (21% exo-tetrahydrodicyclopentadiene

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and 79% RJ-5). At inlet air temperatures of 750°R pronounced differences in combustion efficiencies were observed for the four fuels. As the inlet air temperature was raised to 1250°R, these differences tended to become greatly diminished.

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FOREWORD

This report contains the results of an effort to determine what effect various RJ-5 fuel blends may have on ramjet dump combustor performance. The work was performed in the Ramjet Division and the Fuels and Lubrication Division of the Air Force Aero-Propulsion Laboratory, Wright-Patterson AFB, Ohio, under Project 3012, Task 301212, and Work Unit 30121208. The effort was conducted by R. R. Craig/RJT, J. Petrarca/SFF, J. T. Hojnacki/RJT, and P. L. Buckley/RJT during the period of February to July 1976.

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LIST OF ILLUSTRATIONS

SYMBOLS

A	Area - in^2
f/a	Fuel-to-Air Ratio
F	Thrust Stand Force - lbs.
P	Pressure - psia
S_a	Air Specific Stream Thrust
T	Temperature - °R
ΔT_t	Total Temperature Rise Across Combustor

SUBSCRIPTS

0	Ambient
5	Nozzle Exit
*	Sonic Point
c	Combustor
i	Ideal
t	Stagnation Conditions
exhaust	Exhaust Section Value
ext	Value at Nozzle Outside Diameter
seal	Value at Exhaust Seal Diameter

SECTION I

INTRODUCTION

Current ramjet powered, volume limited missile designs employ a heavy hydrocarbon fuel, RJ-5, in order to achieve maximum range. Operating environments of the missile may require pumping and controlling of the fuel at temperatures in the range of -40°F to -65°F.

The RJ-5 fuel is composed of hydrogenated dimers of Norbornadiene. In the past, the RJ-5 fuel produced in the batch process had a true freezing point around +23°F. A current continuous process development program with the Sun Oil Company indicates an RJ-5 can be produced with a freezing point of -40°F. Additional processing techniques may lower the freezing point to -65°F. The RJ-5 is the only known hydrocarbon which has a volumetric heating value of 160,000 BTU/gallon and is still a mobile liquid at low temperatures.

Hamilton Standard has recently identified the maximum state-of-the-art viscosity for the fuel control as between 400 and 500 c.s. The main disadvantage of RJ-5 is that its high viscosities at low temperatures imposes operational restrictions on the missile system. Two approaches are possible to deal with this restriction. The first is to maintain the temperature of the fuel (by heating) above the value which corresponds to the viscosity limit. The second is to use an RJ-5 blend whose viscosity does not exceed the imposed limit over the temperature environment of the missile system. For many future systems, the environment of the missile has not yet been defined.

The Fuels Branch of AFAPL has been evaluating different diluents with RJ-5 fuel. The most effective one for reducing viscosity while maintaining a high heat of combustion is exo-tetrahydrodicyclopentadiene (exo-THDCPD).

This hydrocarbon was synthesized by Sun Oil Company under Contract F33615-73-C-2022. Its properties are listed in Table 1. Data such as viscosity as a function of weight percent exo-THDCPD for different temperatures has been produced.[1] This data will enable the missile design engineer to perform a trade-off study between missile range and fuel heating requirements based upon the temperature restraints.

The Navy at the Naval Weapons Center has also been developing RJ-5 blends for ramjet systems. The fuel SI-80 (80% RJ-5 and 20% isobutylbenzene) was specifically designed for the MRE. The only guideline used was that the viscosity of the fuel should not exceed 170 c.s. at -40°F. This limit was due to the MRE fuel control system.[2]

This in-house test program was set up to look at what effects the diluents, exo-THDCPD and isobutylbenzene, might have on the combustion performance of RJ-5 fuel blends. Inlet air temperature was varied along with pressure and fuel injection location. Fuel temperature was a constant 70°F.

A follow-on program should look at the effect of very cold fuel, at least -40°F, on combustion and injection characteristics.

SECTION II

EXPERIMENTAL PROCEDURE

A. Test Hardware:

The test hardware for these tests was the large scale, baseline hardware described in Reference 3. The combustor was 12" in diameter and the nozzle throat area was 50% of the combustor area. In addition to our standard fuel injection plane, 4 1/8" from the dump station, fuel could be injected 10 feet upstream of the combustor in the highly turbulent region where the test rig is fed air from twelve 2" flex hoses. Injection here should have produced a uniform mixture to the combustor; however, no measurements were made to verify this assumption, because of a lack of instrumentation for performing the necessary measurements.

B. Test Rig:

The combustor hardware was mounted on a thrust stand designed for measuring absolute levels of thrust. The movable deck of the thrust stand is 14 ft. in length and 4 ft. wide. The deck is suspended from 4 flexures 15 inches long, 4 inches wide and 0.036 inches thick. Calibration of the thrust stand load cell was accomplished by applying a force at the combustor centerline through a reference load cell.

Heated air was supplied from the laboratory's indirect fired furnace through twelve 2" D flex hoses to the combustor hardware. Inlet air temperatures were monitored with chromel-alumel thermocouples, shielded to reduce recovery factor effects. Air flow rates were measured with flange tap, square edge orifice plates, and fuel flow rates were measured with turbine type flow-meters.

In order to maintain a choked nozzle while operating the combustors at sub-atmosphere pressures, the nozzles were connected to the laboratory

exhauster system by means of a flexible rolling seal. The exhaust system was maintained at approximately 3 psia. Use of the seal required that all nozzles be water-cooled.

Data was recorded on magnetic tape at a rate of 40 channels per second via a Hewlett-Packard 2012B digital data acquisition system.

C. Combustion Efficiency:

The definition of combustion efficiency used throughout this report is:

$$\eta_c = \frac{\Delta T_t}{\Delta T_{ti}}$$

where ΔT_t is the total temperature rise across the combustor as computed from the thrust measurement and ΔT_{ti} is the ideal total temperature rise for the measured fuel-to-air ratio as computed from equilibrium chemistry calculations. Since absolute thrust is measured, corrections for ambient pressure acting on the hardware and exhauster seal forces must be made in order to obtain the sonic air specific stream thrust, S_a*. These corrections are:

$$S_a^* = \frac{F}{W_a} + \frac{P_o A^*}{W_a} + \frac{(P_o - P_{exhaust})}{W_a}\left[\frac{(A_{seal} + A_{ext})}{2} - A^*\right]$$

Three-dimensional tables of S_a* versus T_{t5} and P_{t5}, computed by means of equilibrium chemistry routines, are then used to determine T_{t5} from S_a* and P_c.

SECTION III

DISCUSSION & RESULTS

For these tests, four different fuels were used, JP-4, RJ-5, SI-80, and HDF-2. The test matrix consisted of three different inlet air temperatures of approximately 750°R, 1000°R and 1250°R with two different air flow rates which would yield combustor pressures of approximately 16 psia to 10 psia. Fuel flow was then varied to produce increments in fuel-air ratio of approximately 0.005.

The fuel HDF-2 is composed of 79% RJ-5 and 21% exo-THDCPD. Its properties are shown in Table 2. This fuel was tailored through blending to have a viscosity around 400 c.s. at -40°F. In the final analysis, its viscosity was actually 355 c.s. This translates into a viscosity reduction of 79.1% over the baseline RJ-5. The volumetric heating value of HDF-2 is only 3.3% lower than the RJ-5.

The fuel, SI-80, is composed of 80% RJ-5 and 20% isobutylbenzene and was supplied to AFAPL by B. Burdette of NWC. Its properties are also listed in Table 2. The volumetric heat of combustion of SI-80 is approximately 1,000 Btu/gallon lower than reported in literature by the Navy. The Navy value, 154,000 Btu/gallon, was based on one data point and may be in error.[4] The viscosity reduction of SI-80 over RJ-5 at -40°F is 89.5%. Its volumetric heating value is 5.6% lower than RJ-5.

The objective of these tests was not to obtain high combustion efficiencies but rather to be able to discern differences in performance of the fuels when inlet air temperatures and air flows were changed. This is best accomplished when efficiencies are on the order of 70% to 80% and not when they are 95%.

Figure 1 compares performance obtained for the four fuels at a nominal air flow of 8 lb/sec and a nominal inlet air temperature of 750°R. At low fuel-air ratios, all four fuels yield similar performance. At a fuel-air ratio of about 0.04, the combustor went into a radial mode combustion instability for all fuels except the RJ-5. This instability ceased for the HDF-2 at a fuel-air ratio of 0.05 and .055 for the SI-80. Performance was then similar to that for the RJ-5.

Figure 2 is a comparison of the performance obtained with the four fuel blends under pre-mixed conditions. Inlet air temperature and air flow are similar to those of Figure 1. In comparing Figures 2, 4 and 6, it is seen that the low temperature pre-mixed data for the RJ-5, SI-80 and HDF-2 is not consistent with the 1000°R and 1250°R data. For the pre-mixed JP-4 data, performance increases as inlet air temperature increases and the fuel-air ratio, at which the steep rise in performance occurs, decreases. At 1000°R and 1250°R with RJ-5, SI-80 and HDF-2, performance is slightly less than the JP-4 performance, but the low temperature data is higher than the JP-4 data. The reason for this reversal in trends is not known.

Figures 3 and 5 are comparisons for injection of the fuels near the dump at inlet air temperatures of 1000°R and 1250°R, respectively, and appear to be consistent with Figure 1. Figures 7, 8, 9 and 10 are cross plots of the data of Figures 1, 3 and 5 to show the changes experienced for each individual fuel, with inlet air temperatures. With all fuels, except RJ-5, combustor screech was audibly detected. The severity of the instabilities decreased with increasing inlet air temperatures and were minor in terms of danger of damage to the combustor.

Figures 11, 12 and 13 compare the performance obtained at air flows of 5 lb/sec for the three inlet air temperatures. Performance is generally lower than that obtained at the higher air flow and is dramatically reduced for the low inlet air temperature case. Combustor instabilities have disappeared, at the low inlet air temperature, for all the fuels except the JP-4.

SECTION IV

CONCLUSIONS

1. The diluents exo-THDCPD and isobutylbenzene appear to have very little effect on combustor performance for room temperature fuels.

2. The fuels, HDF-2 and SI-80, gave a viscosity reduction over RJ-5 of 79.1% and 89.5%, respectively. The volumetric energy penalty is 3.3% for HDF-2 and 5.6% for SI-80.

3. A discrepancy of approximately 1000 BTU/gal in the volumetric heat of combustion reported in literature and obtained through testing was found for SI-80.

4. Comparison combustion tests still need to be performed with cold fuels, but little difference should be evident as long as the atomization of the fuel by the injectors is sufficient to ensure rapid vaporization of the fuel droplets.

TABLE 1. Properties of Exo-THDCPD

Formula	$C_{10}H_{16}$
Purity, wt %	99
Specific Gravity 60°/60°F	0.939
Net Heat of Combustion	
BTU/lb	18,105
BTU/gal	141,563
Viscosity, cs	
@ 100°F	2.24
0°F	8.02
-40°F	18.00
-65°F	36.49
Flashpoint, °F	132

TABLE 2. Properties of High Density Test Fuels

PROPERTIES	HDF-2	SI-80	RJ-5*
Formula	$C_{12.9}H_{17.7}$	$C_{13.0}H_{17.2}$	$C_{14.0}H_{18.3}$
Specific Gravity 60°/60°F	1.0499	1.0305	1.0870
Net Heat of Combustion			
BTU/lb	17,922	17,823	17,907
BTU/gal	156,702	152,957	162,104
Viscosity, cs**			
@100°F	8.3	4.7	13.9
0°F	72.0	37.0	220.0
-40°F	355.0	178.0	1700.0
-65°F	1,570	745.0	12,057

* Ashland Batch 2 for Comparison

** HDF-2 and SI-80 Data Provided by B. Burdette

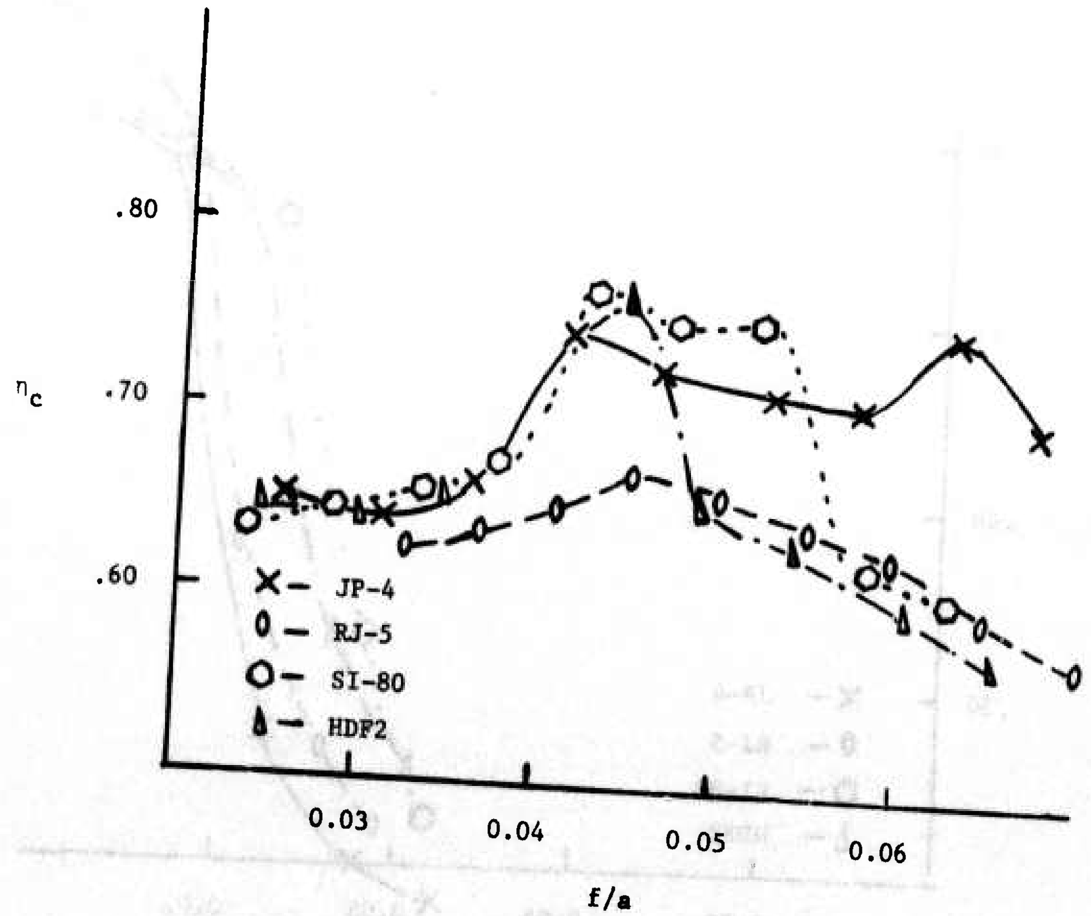

Figure 1 - Comparison of Fuel Blend Performance

T_{T_2} = 772°R

P_C = 16 psia

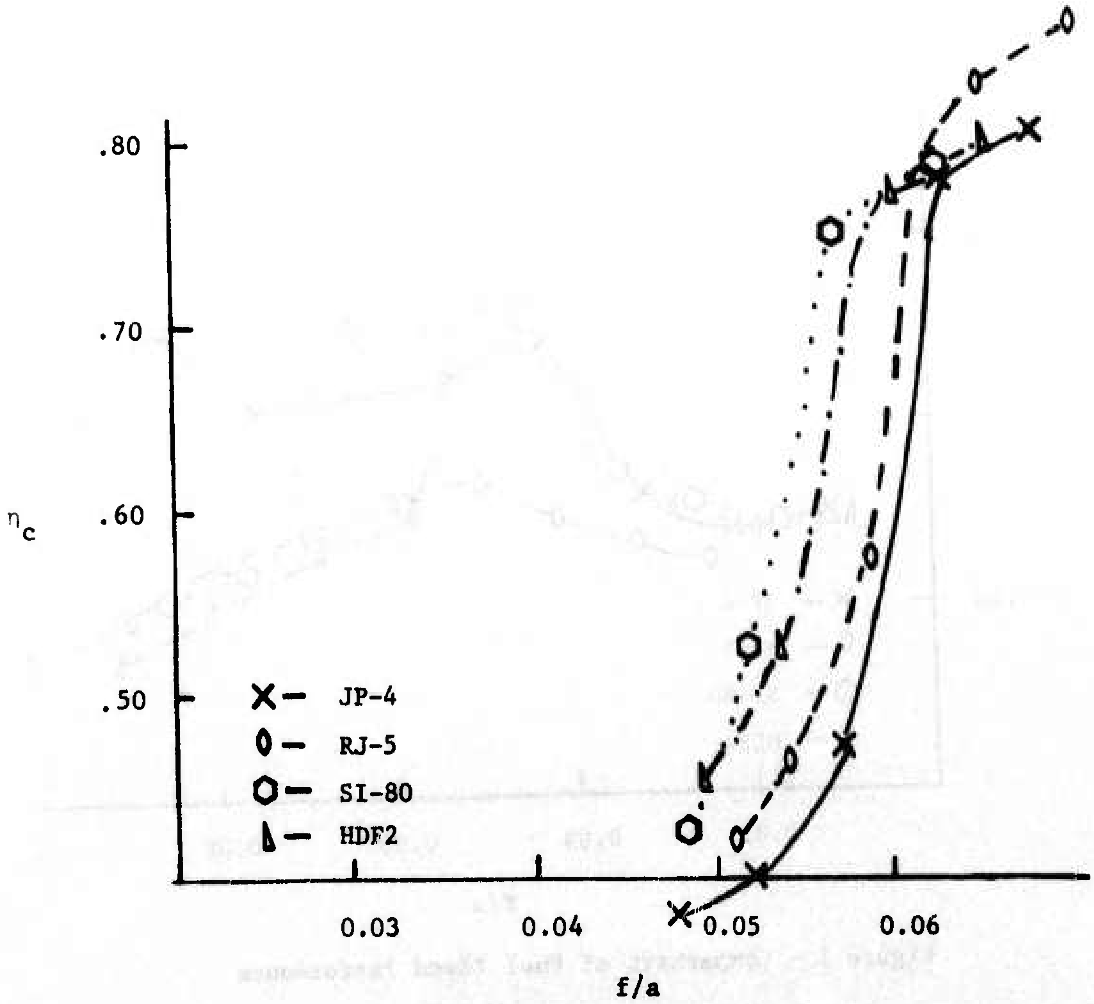

Figure 2 - Comparison of Premixed Fuel-Air Performance for Fuel Blends

$T_{T_2} = 768°R$

$P_C = 16$ psia

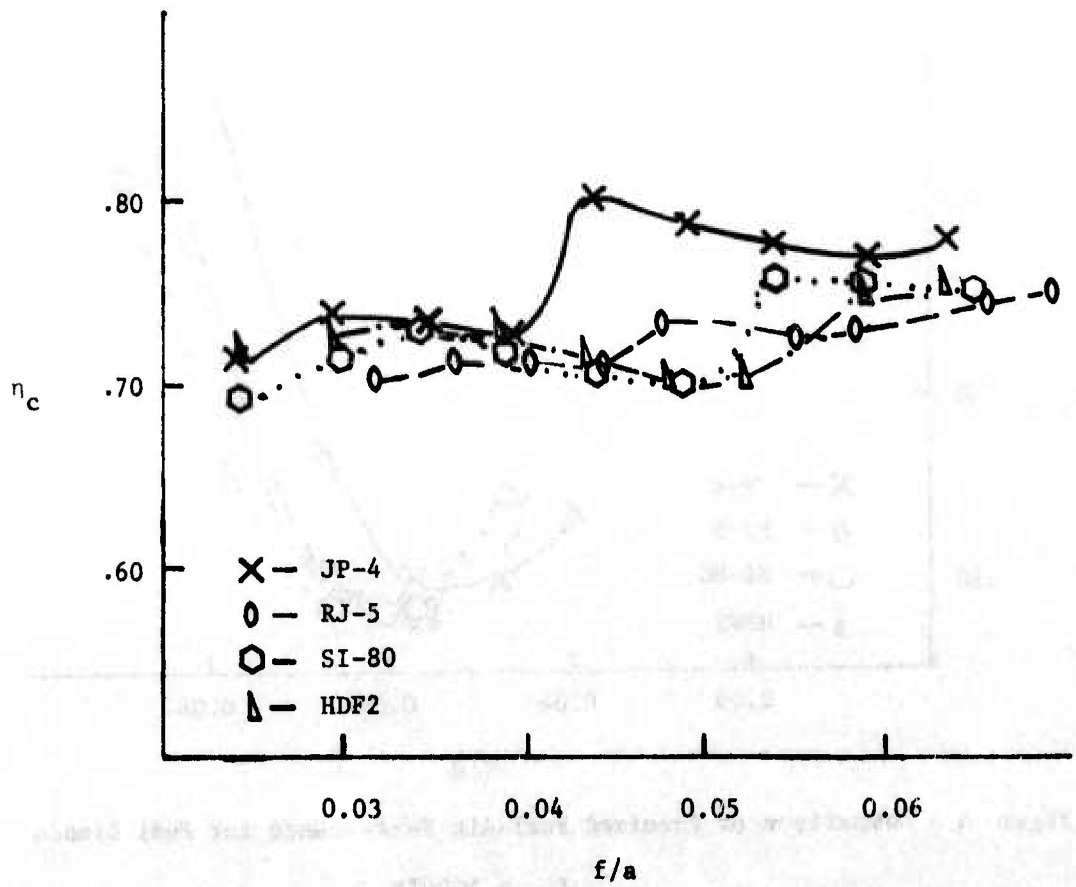

Figure 3 - Comparison of Fuel Blend Performance

$T_{T_2} = 1012°R$

$P_C = 16$ psia

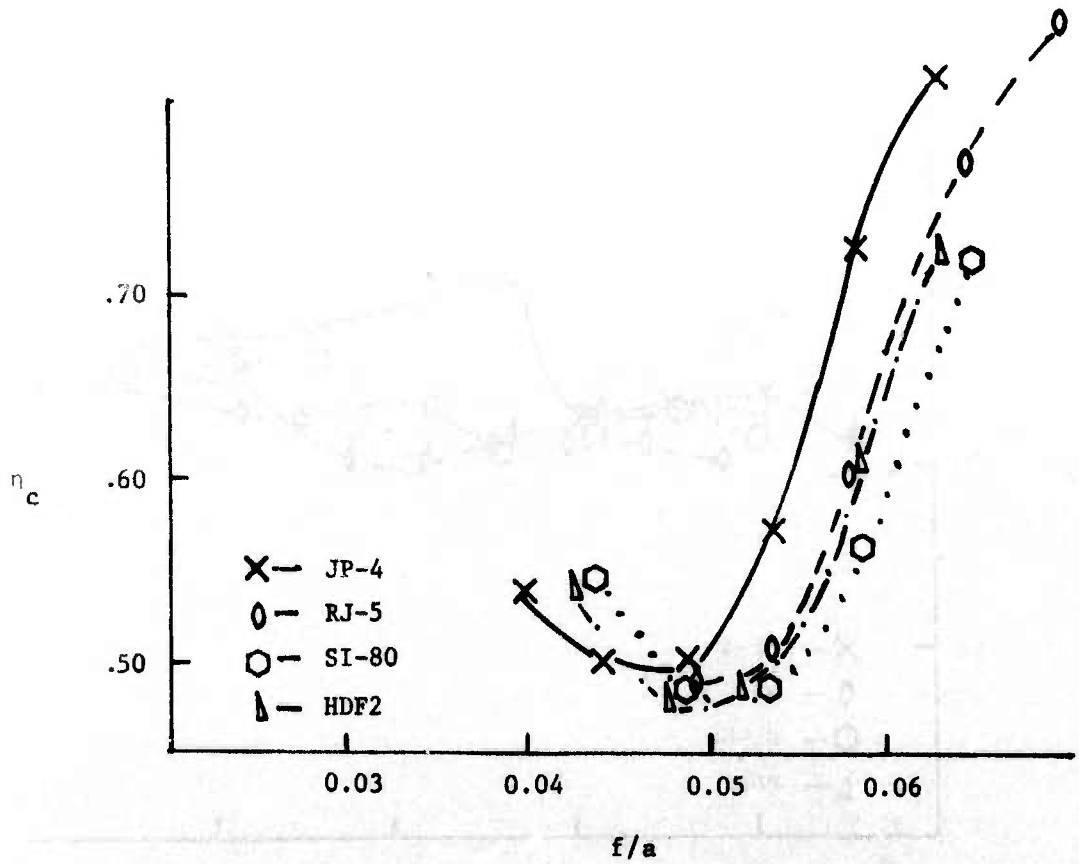

Figure 4 - Comparison of Premixed Fuel-Air Performance for Fuel Blends

T_{T_2} = 1000°R

P_C = 16 psia

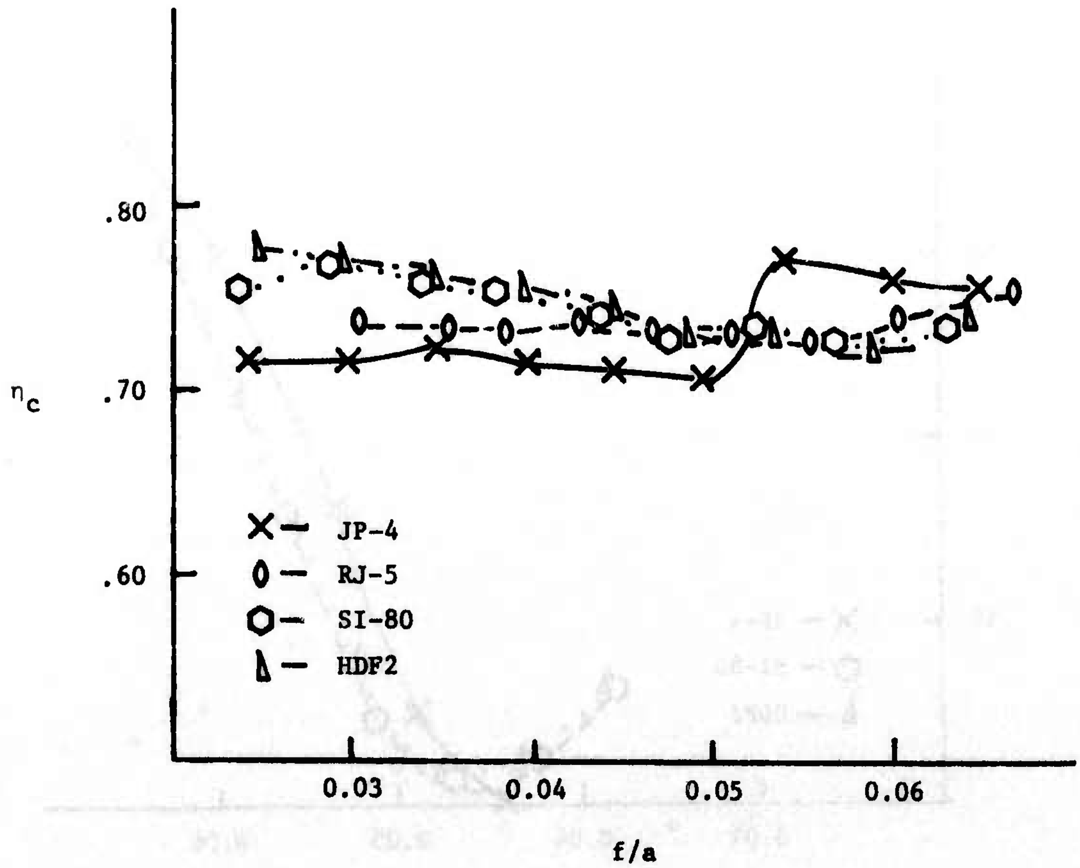

Figure 5 - Comparison of Fuel Blend Performance

T_{T_2} = 1238°R

P_C = 16 psia

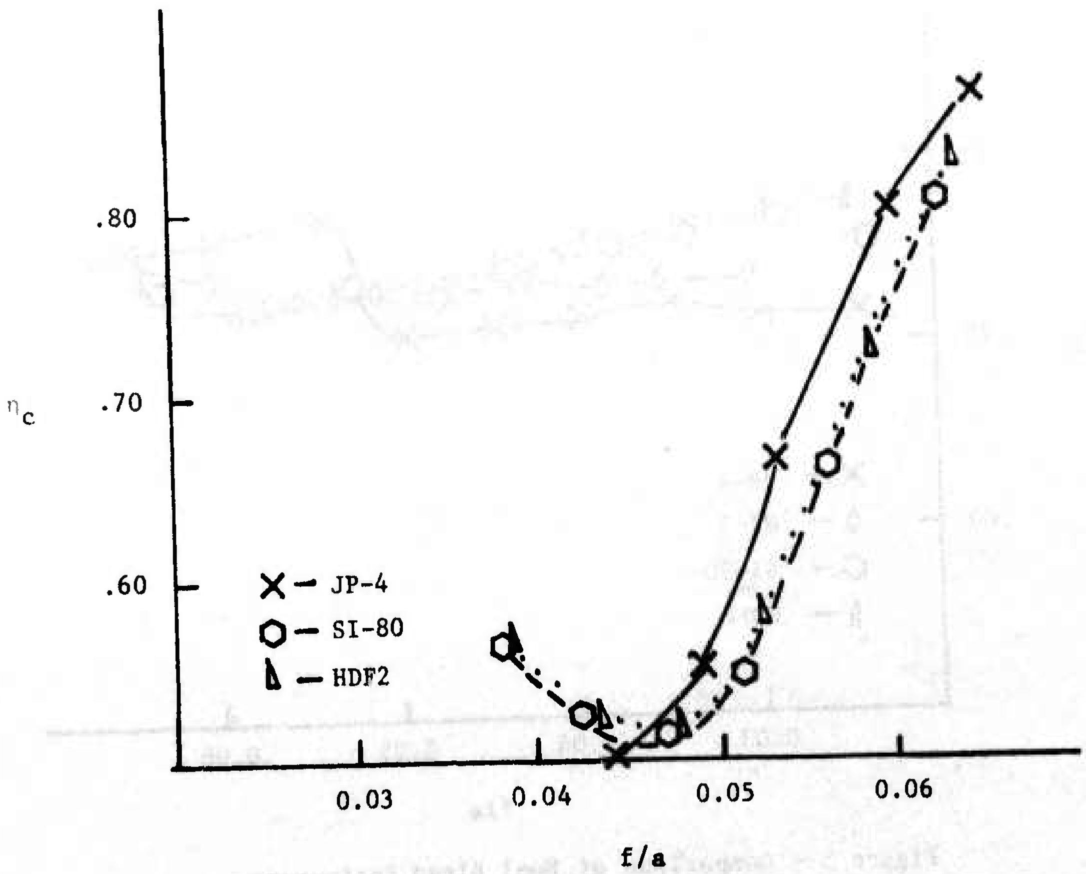

Figure 6 - Comparison of Premixed Fuel-Air Performance for Fuel Blends

T_{T_2} = 1210°R

P_C = 16 psia

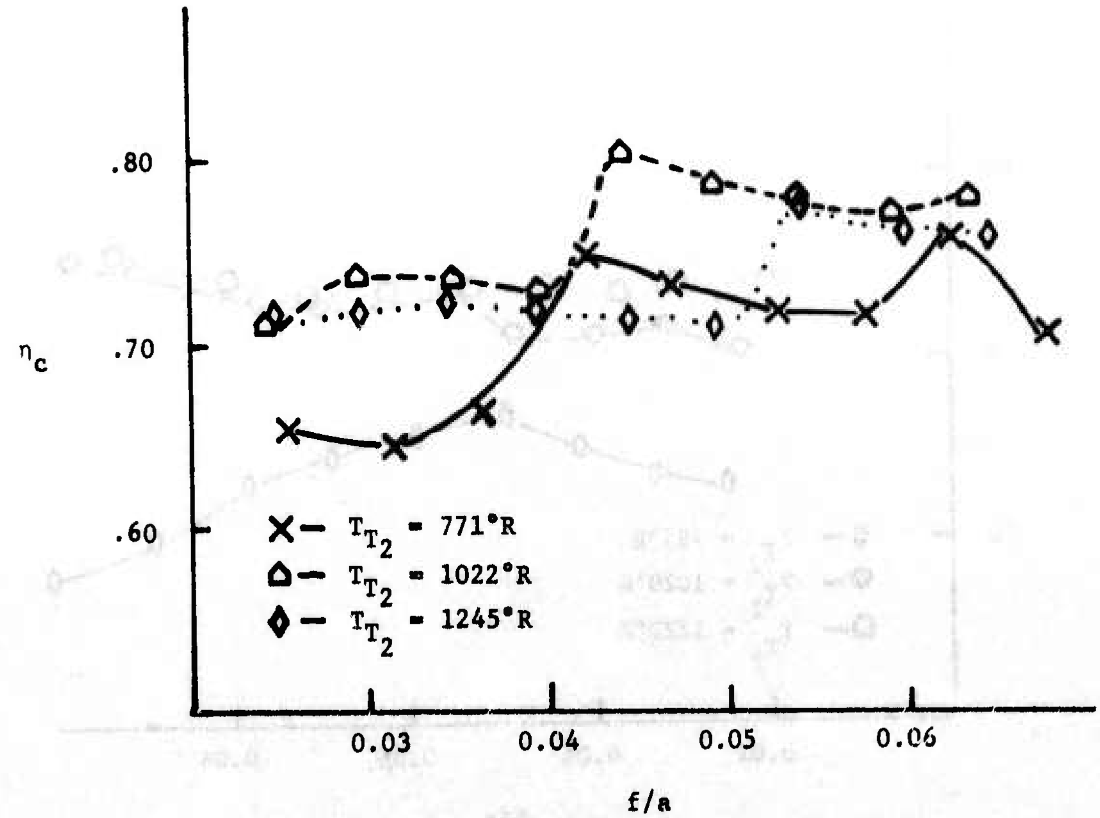

Figure 7 - Effect of Inlet Air Temperature on JP-4 Combustion

P_C = 16 psia

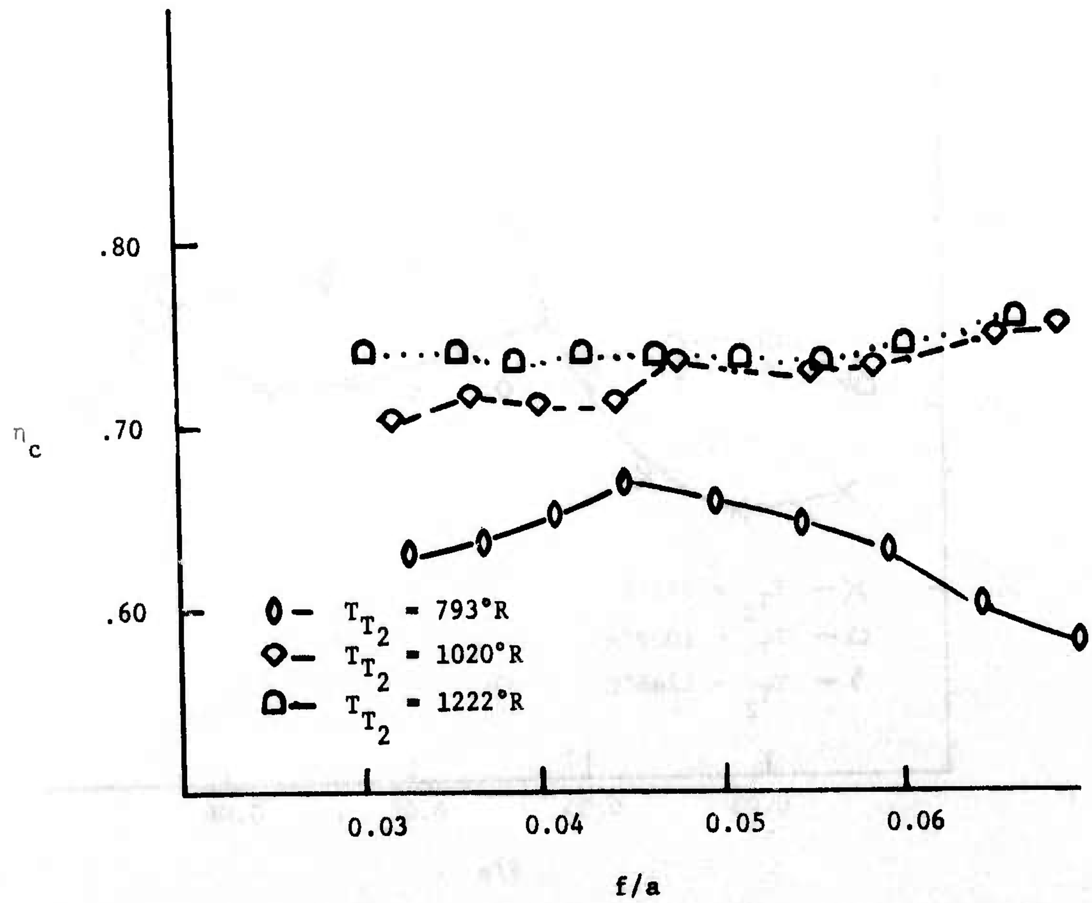

Figure 8 - Effect of Inlet Air Temperature on RJ-5 Combustion

P_C = 16 psia

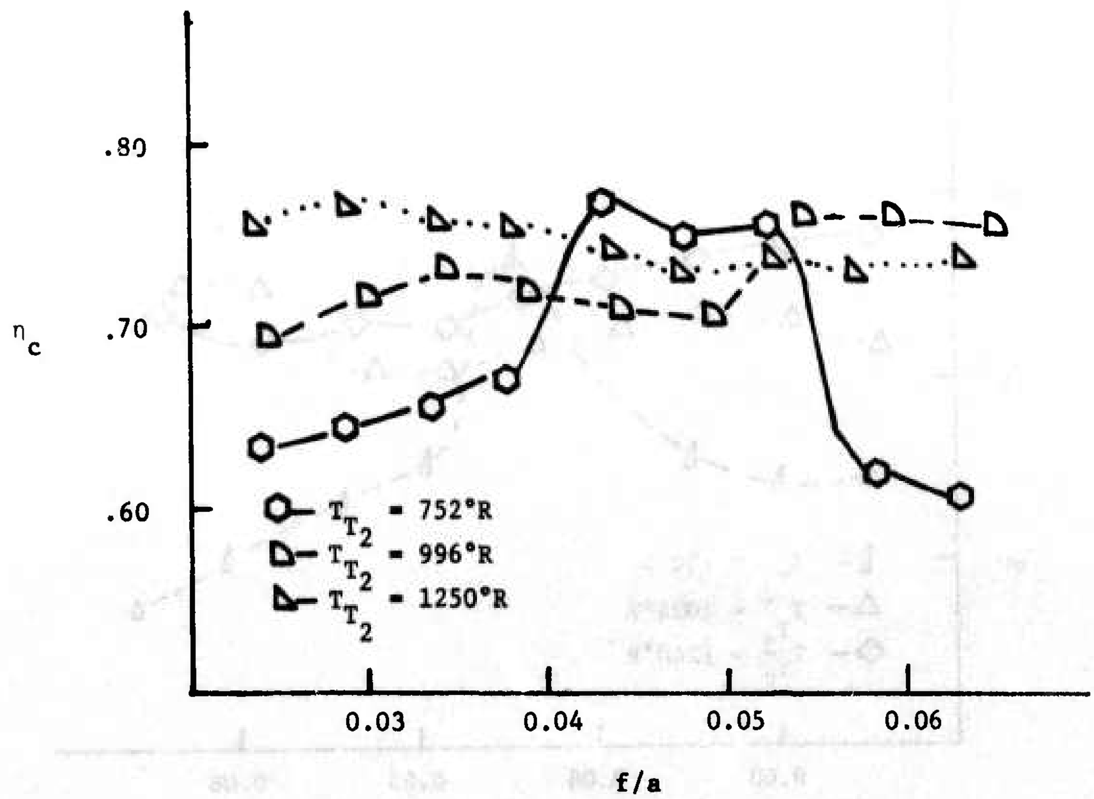

Figure 9 - Effect of Inlet Air Temperature on SI-80 Combustion

P_C = 16 psia

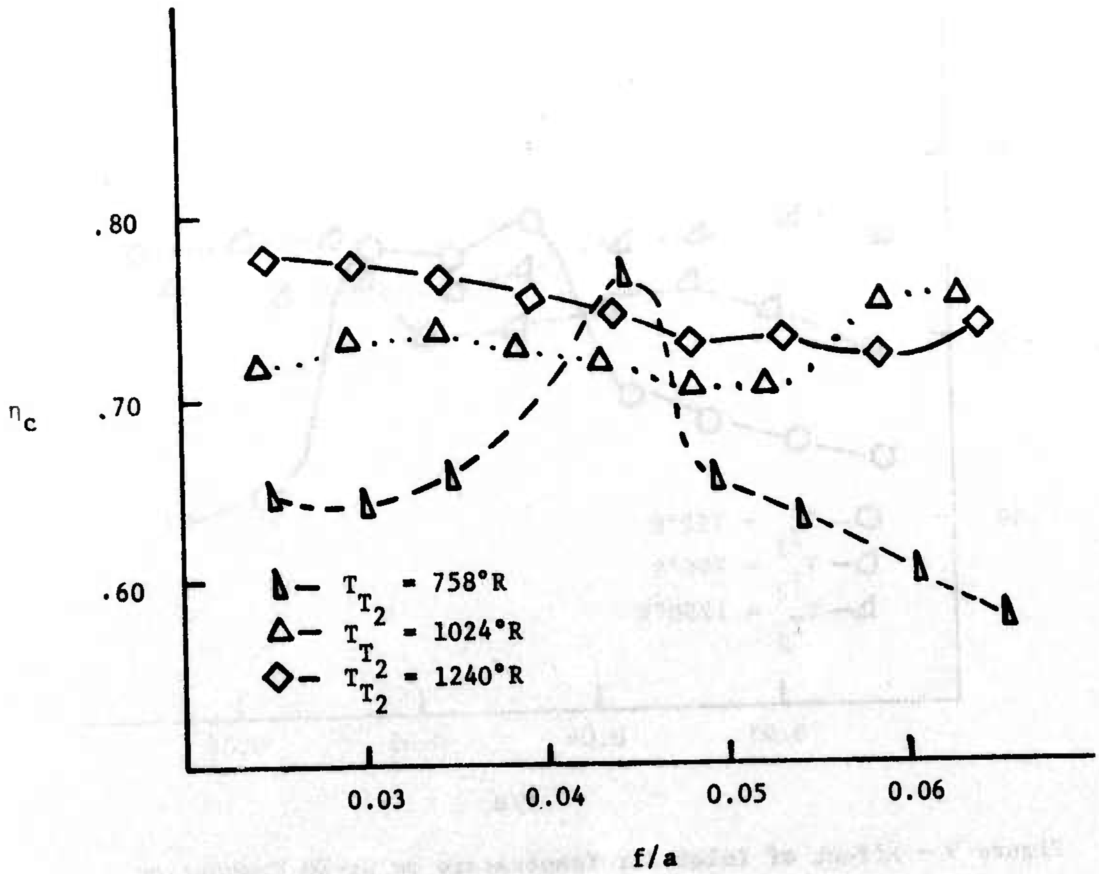

Figure 10 - Effect of Inlet Air Temperature on HDF2 Combustion

P_C = 16 psia

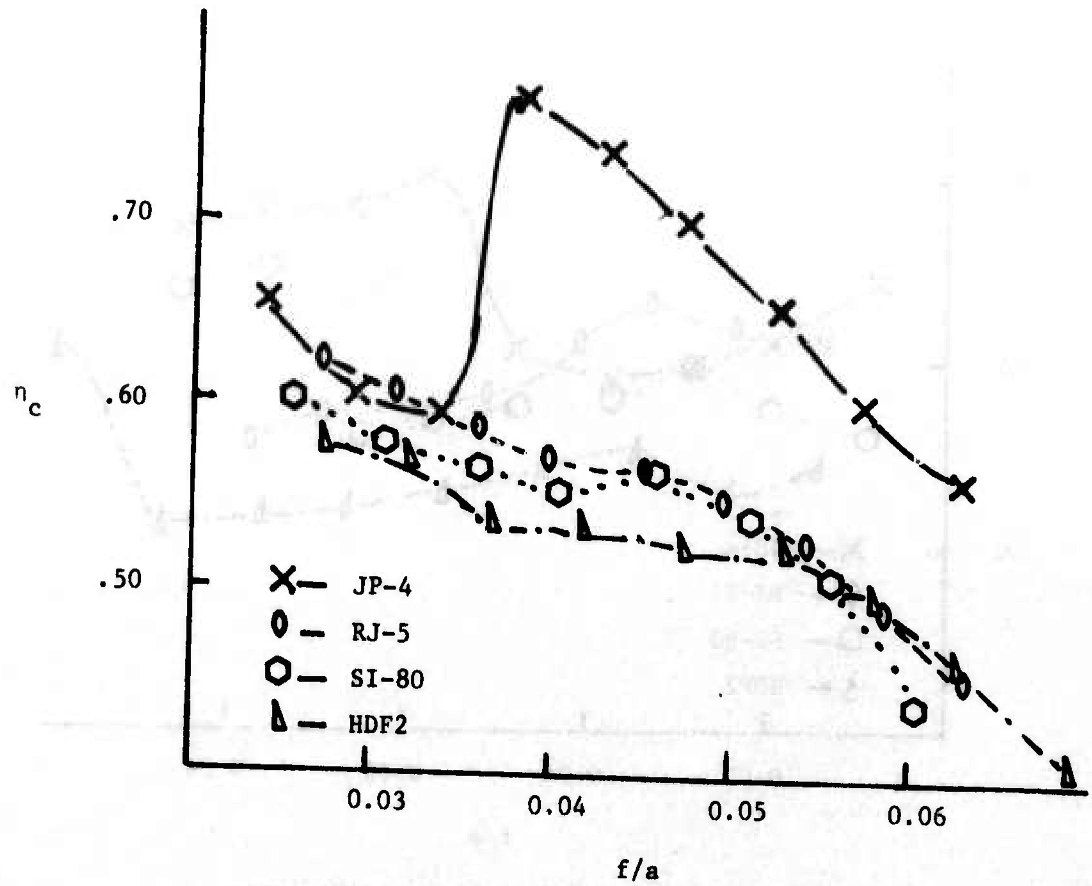

Figure 11 - Comparison of Fuel Blend Performance

T_{T_2} = 768°R

P_C = 10 psia

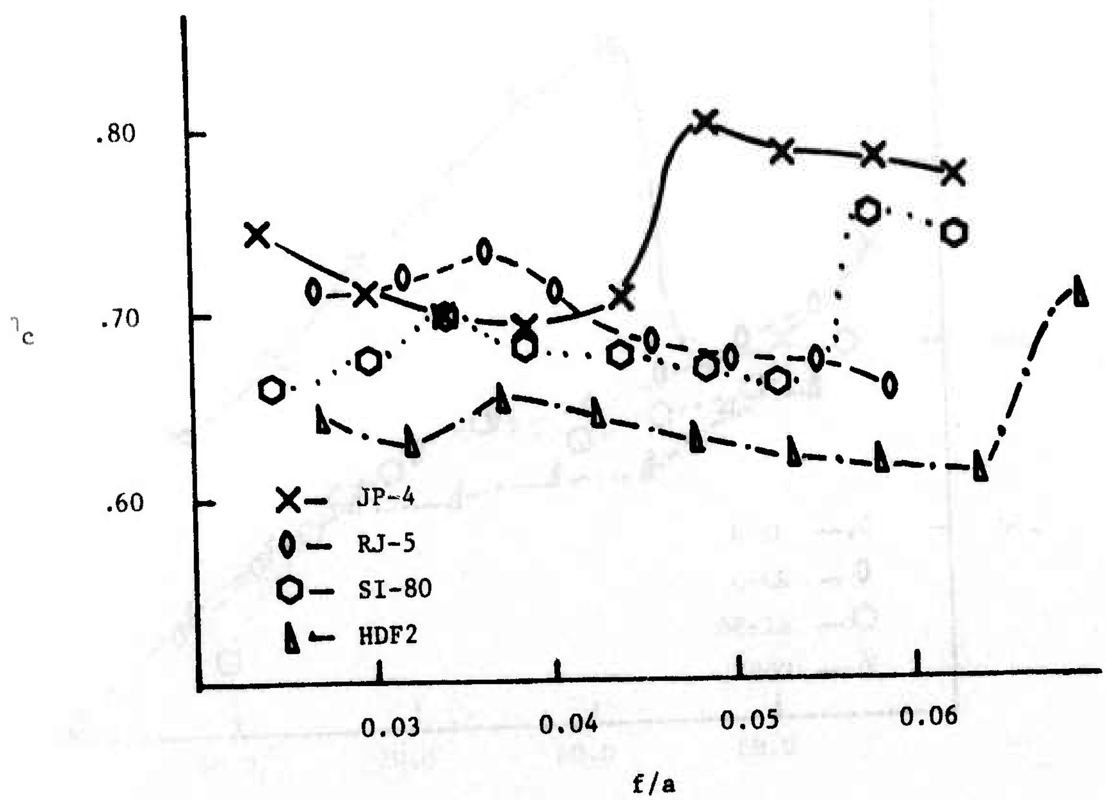

Figure 12 - Comparison of Fuel Blend Performance

$T_{T_2} = 992°R$

$P_C = 10$ psia

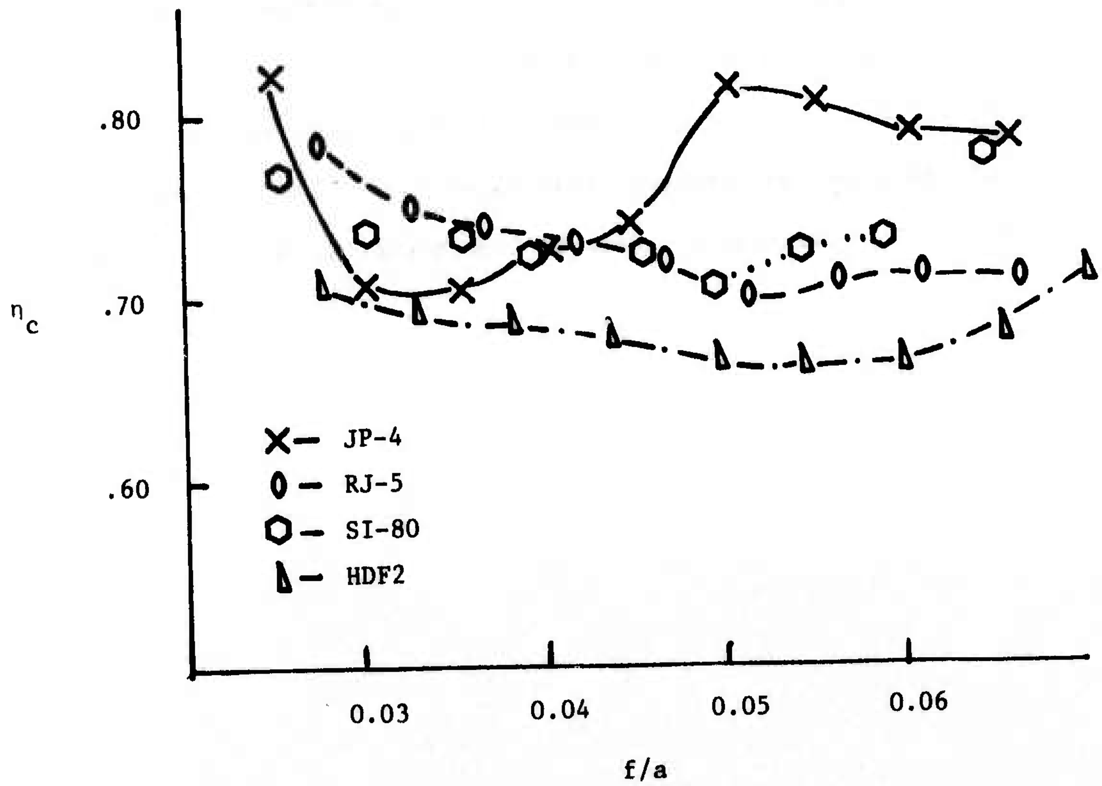

Figure 13 - Comparison of Fuel Blend Performance

T_{T_2} = 1248°R

P_C = 10 psia

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